Monte Carlo Event Generators

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Abstract.
Every neutrino experiment requires a Monte Carlo event generator for various purposes. Historically, each series of experiments developed their own code which tuned to their needs. Modern experiments would benefit from a universal code (e.g. PYTHIA) which would allow more direct comparison between experiments. GENIE attempts to be that code. This paper compares most commonly used codes and provides some details of GENIE.

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INTRODUCTION

Monte Carlo event generators (MCEG) are a key part of every neutrino experiment. As detailed by Gallagher [1], they are needed to design experiments, develop detection algorithms, and calculate systematic errors. Although acceptance is large, the efficiency for detecting hadrons is often small or very energy dependent (e.g. water Cerenkov detectors). There are also special cases where a measurement is sensitive to final state interactions (FSI) in the nuclear environment, e.g. measuring the neutrino beam energy for quasielastic neutrino (QE) reactions when pion production followed by pion absorption can mimic the QE interaction in all existing detectors.

The irony is that although MCEG's are able to calculate essentially any process for neutrino interactions in all nuclei, there is almost no neutrino data to validate the underlying algorithms. Older experiments were able to run with hydrogen and deuterium bubble chambers. Therefore, moderate quality neutrino data for nucleon targets is available at a variety of energies. Since the cross section is large at very high energies, the deep inelastic scattering (DIS) process for neutrinos is well understood. At ν energies of a few GeV, modelers are often forced to rely on fits to inclusive electron scattering data for nuclear structure and to pion scattering and absorption data for FSI. Experiments (e.g. K2K and MiniBOONE) have introduced empirical factors to change the model results to match their data.

OVERVIEW OF MODELS

There are about 6 nuclear MCEG's available. Although GiBUU [2] and FLUKA [3] have excellent physics models, they are too computer-intensive and carry a license difficult to satisfy, respectively. They are not used by any neutrino accelerator experiment. NuWro [4] is still under development and is also not used in any experiment to date, but has the best nuclear structure [5] and an independent DIS model. NUANCE [6] reached maturity many years ago due to the work of Casper (UCI). It has been used by MiniBoone, KamLand, and SNO. No new version of NUANCE has been released for a number of years and all adjustments are made by the MiniBOONE collaboration. Thus, NEUT [7] and GENIE [8] are the most often used codes today. NEUT [7] is maintained by Hayato (ICRR) and SuperKamiokande and T2K collaborators; it is the primary MCEG for all experiments using the SuperKamiokande detector and SciBoone. GENIE is led by Andreopoulos (RAL) and a comparatively large group of experimenters and theorists contribute. It is used in MINOS, MINERνA, NOνA, MicroBoone, T2K, INO, LBNE, and ArgoNEUT experiments.

The 3 MCEG's used in present experiments use similar physics models. All use the Fermi gas nuclear structure model; this has the advantage of easy application to all nuclei. Inclusive electron scattering data shows good validity of the model whenever quasieleastic processes dominate, but can be off by large factors when nuclear correlation dominate and have been shown to be off by $\sim$20% at the QE peak in shell model calculations. All use similar models for the QE interaction and the resonant pion production for nucleons [9]. Although all use intranuclear cascade (INC) models for FSI, the underlying assumptions of the models have significant differences [11]. All use the same calculation of the coherent pion production cross section [10], but have different implementations. The model comparison study put together for NUINT09 [12] for ν_μ carbon interactions at $\sim$ 1 GeV shows interesting results. Although NEUT and GENIE ostensibly use the same Rein-Sehgal [10] model for coherent processes, they are different by a factor of 2 in total cross section. Each are in turn significantly larger than recent theoretical calculations. The MiniBoone experimenters decrease the NUANCE prediction to match their data. The 'regular' pion production process shows even more variation. The MCEG models differ significantly from the theoretical models in shape because the former have devoted more effort to FSI and the latter have worked harder on the nuclear structure effects. The MCEG models also differ significantly among each other due to different model implementations. The QE total cross sections from both MCEG and shell model codes are very similar (when using the same axial form factor) except at threshold where kinematic choices vary greatly.

GENIE FEATURES

GENIE [8] attempts to be compatible with any neutrino experiment at energies 100 MeV-500 GeV.. The code is publicly available from http://www.hepforge.org. It uses modern C++ coding techniques and standard libraries such as ROOT, PYTHIA, LIBXML, and LHAPDF. A lengthy user's manual is available at http://genie-mc.org or at hepforge. Features implemented for MINOS and T2K were designed for general use.

All neutrino events are chosen according to geometry which can be specified as a ROOT geometry file. Although the nuclear model is simple (relativistic Fermi gas), it can easily be generalized to all nuclei. Thus, detector materials can be made from any isotope and events will be created according to the product of mass density and cross section. The simplicity of the nuclear model also allows a spline file of all required cross sections to be made before the simulation. A multidimensional look-up table is then used to generate events.

The beam flux can be specified in a variety of ways - ascii file, ROOT file (with or without angles and position defined), or a simple formula. NUMI (MINERνA and MINOS) and JPARC (T2K) flux files come with the code.

The principal vertex interaction is chosen from a user-defined list and many model parameters (e.g. Fermi momentum) can be changed in an external file. A growing number of validation programs are available to the user. Cross sections used for neutrino event generation can be viewed with NuValidator. A few new validation tools will be available in upcoming releases. An extensive set of hadron nucleus cross sections with the means to compare with any hadron simulation has been developed. Comparisons with a variety of DIS cross section data and inclusive electron scattering data (http://faculty.virginia.edu/qes-archive/) will be possible.

Many experiments use reweighting to test for systematic errors and various 'what if?' scenarios. GENIE has a structure for this work and has the ability to adjust various parameters. Right now, the cross section scale of each channel, various internal variables such as the axial mass, and various FSI quantities can be varied. This list will grow as more experiments adopt and enhance the code.

CONCLUSIONS

Various MCEG codes are in active use in experiments and others are available. Many of the underlying physics models are similar because they need simple models that describe a wide range of data well. Aa a result, the total quasielastic cross sections are very similar. On the other hand, the kinematics treatment at threshold has considerable variation. An even more basic divergence is aeen for pion production cross sections where the results are very different because hadronic model choices are made.

GENIE tries to be the universal MCEG and has been chosen by most recent neutrino experiments. It has many features which make it readily adaptable. A new version (2.8) is expected to have enhanced user features. New theoretical models are in development.

MCEG codes must continue to integrate the best available theoretical results and validate their models against new data. The significant increase in neutrino-nucleus cross section data in the last few years (MiniBoone, SciBoone, and MINERνA) is very welcome.

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